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AN APPROACH TO A GENERAL THEORY OF FATIGUE

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The proposal addressed the problem that we are still years away from a general theory of fatigue, i.e., the capacity to predict accurately crack nucleation and propagation behavior with respect to cyclic stress amplitude, component geometry cyclic frequency, material nature, temperature and environment. Although a century of testing has accumulated an enormous body of results, designers still have to resort to testing on a major scale when they attempt a new structure. A reliable theory of fatigue would bring considerable savings to such ventures.

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FINAL REPORT

1. **ARO Proposal Number:** 9329-MC

2. **Period Covered by Report:** 15 September 1971 to 31 March 1975

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5. **Author of Report:** Campbell Laird, Professor, [redacted]
Principal Investigator.

6. **Statement of Problem:**

The proposal addressed the problem that we are still years away from a general theory of fatigue, i.e., the capacity to predict accurately crack nucleation and propagation behavior with respect to cyclic stress amplitude, component geometry, cyclic frequency, material nature, temperature and environment. Although a century of testing has accumulated an enormous body of results, designers still have to resort to testing on a major scale when they attempt a new structure. A reliable theory of fatigue would bring considerable savings to such ventures. Since a reasonably complete theory of fatigue is well beyond the resources of a single institution, the principal investigator selected the following aspects of the fatigue problem for detailed treatment:

a) Cyclic Stress-strain Response: What are the mechanisms of cyclic deformation in two phase materials? And in long life fatigue in single phase materials? The approach was to compare the cyclic stress-strain response and dislocation microstructures of simple, well-controlled, age-hardened aluminum alloys, and of copper single crystals, cycled both under constant strain amplitudes and varying amplitudes.

b) Crack Propagation: What is the relationship between cyclic stress-strain response and crack propagation? The approach was to employ Tomkin's theory as a test of the relationship between life and cyclic deformation. Tomkin's theory contains major conceptual difficulties but it represents a first step in tying together these two aspects of the fatigue problem and at least must be regarded as an interesting empirical correlation. A subsidiary aim was to make a contribution towards understanding the role of microstructure in crack propagation, especially in aluminum alloys.

c) Crack Nucleation. What is the mechanism of crack nucleation at high cyclic strains and at low cyclic strains? How do these relate to cyclic deformation?

The approach was to test a theory of crack nucleation at high strains based on a plastic instability mechanism, and at low strains, to measure the detailed structure of persistent slip bands in copper single crystals by two beam interferometry. A ferroelastic alloy was also studied to explore the affect of slip band reversibility on crack nucleation.

Results

a) Cyclic Stress-Strain Response

i) Aluminum Alloys Cycled at Constant Strain Amplitudes

Specimens of solution-treated Al-4% Cu alloy were cycled in that condition, and also after ageing to produce, separately, coherent θ'' and θ' precipitates. Constant plastic strain was used as the mode of control. The solution treated alloy (which actually contained GPI zones as a result of room temperature ageing and cycling) and that containing θ'' showed large degrees of cyclic hardening during the early stages of the tests, but they subsequently underwent work softening. Although such softening had been widely claimed, this was its first unequivocal demonstration. These hardening and softening processes were investigated by a variety of phenomenological experiments, and by scanning and transmission electron microscopy. The hardening was interpreted by the concepts of unidirectional deformation and softening by a disordering hypothesis, a new application with respect to fatigue. In view of the widespread belief in precipitate resolution explanations for softening, the principal investigator has observed a mixed reception of the disordering hypothesis. However, no contrary evidence has been found and support is now coming from unexpected sources, e.g., J. W. Mitchell's investigation of Cu-Al-Pd alloys.

The alloy containing θ' precipitates showed much lower degrees of hardening and no softening. By application of unidirectional hardening mechanisms such as "geometrically-necessary" dislocations, the mechanism of cyclic hardening was explained, and we determined how the cyclic response approached that of single phase materials when the interparticle spacing was equal to, or greater than, the self-trapping distance of dislocations.

The results of these investigations were published in references 1 and 2 (Section 8), and their implications for Kramer's ideas of surfaces hardening were explored in reference 3. The relevance of the results for fatigue in general was treated in two review articles (5, 6).

ii) Aluminum Alloys Cycled Under Varying Strain Amplitudes

The aluminum alloys described above were also subjected to variable strain cycles, in the form of incremental tests, i.e., the strain was increased and then decreased in alternating fashion. This form of testing was chosen because engineering investigations of cumulative damage have shown that the cyclic response for incremental tests is similar to that for random loading. However, no investigations from the point of view of materials science have hitherto been made of this interesting problem. We found a marked similarity between the cyclic response of the incremental test and that of the constant amplitude tests when the alloy contained θ''. Softening even occurred at roughly equivalent values of accumulated strain. However, for the alloy containing θ' precipitates, the flow stresses observed in the incremental tests lay considerably below those of the constant amplitude tests. These results were interpreted in terms of dislocation pairing processes acting to reduce internal stresses associated with geometrically necessary dislocations.

Since varying amplitude processes in cyclic response are also unknown for pure metals, a parallel study was made for polycrystalline pure copper. The electron microscope observations for this part of the program are not yet complete and thus no attempt has yet been made to publish the results of this part of the program (7, 8).

iii) Strain Localization in Cyclic Deformation of Copper Single Crystals

The localization of plastic strain into macroscopic groups of persistent slip bands was determined by two beam interferometry on copper single crystals strain - cycled into saturation. A single slip orientation was used. The macroscopic bands were observed to traverse the whole cross-section and adopt a sufficient volume fraction of the gauge length to accommodate the applied strain at a constant stress level up to a strain of ± 0.01, i.e., to this strain, the cyclic stress-strain curve is horizontal. The bands undergo complete reversibility of plastic strain with load reversibility. Although overall, surface slip steps form in proportion to the applied plastic strain, individual steps are not always completely reversed, leading to the rapid formation of a notch-peak topography within the bands. After saturation is reached, all the plastic strain is carried by the bands, and the whole gauge-length is active only during rapid hardening prior to the onset of saturation. The dislocation structure of the persistent slip bands was determined, permitting a critcal assessment of the various mechanisms proposed for saturation in low-strain cyclic deformation. Thus the Feltnerian flip-flop model of dislocation dipoles was discarded, as was Kramer's theory based on cyclic hardening of the surface. In addition, the whole basis of Kramer's theory was undermined by the cyclic stress-strain measurements (10). Partly from the ideas of Grosskreutz et al., an adequate model of saturation was found upon the cooperative movement of primary links, originating in the cell walls of the persistent bands and moving between the walls, but impeded in their motion by point defect clusters and small dislocation debris.

The above investigation was found to be very difficult because of the need for extreme precision in crystal orientation, both axially and in the faces of the crystal, the specular nature of those faces and in the use of MTS and Instron machines in carrying out complex tests. A special tribute is due to the student J. M. Finney, in accomplishing this work (10).

During the course of this investigation, an opportunity was presented to study history dependent aspects of cyclic response, with little additional extra work. Specifically, the problem was addressed of why observers have reported history dependence in wavy slip metals and others have reported history independence. We found that dislocation structures resulting from very large prestrains (> about 60%) could not be work softened to the history independent condition by cyclic strains regularly employed in high strain fatigue (11). Transmission electron microscopy showed that large misorientations across dislocation cell walls were retained into saturation, and the resulting dislocation links were shorter (and the flow stresses thus larger) than those observed in less severely prestrained metals (11). For less severe prestrains, history independence of cyclic response is the rule of course.

b) Crack Propagation

Crack propagation was studied indirectly in the present investigation through general observations on fatigue damage mechanisms in simple push-pull specimens cycled at high strains. To understand the role of microstructure Al-4% Cu alloy was studied as a function of particle type and spacing by means of scanning and transmission electron microscopy. When the microstructures contained precipitates penetrable by dislocations, intense intragranular slip bands formed and, as in low strain fatigue, became the sites of crack nucleation and Stage I propagation. With the addition of impenetrable particles, slip was dispersed homogeneously; consequently, crack nucleation and Stage I propagation shifted to the grain boundaries. Stage II crack propagation occurred transgranularly in both types of microstructure. Since both cyclic response and fracture mechanisms were securely established in the same material, it was then possible to test Tomkins' model of fatigue crack propagation (life prediction) in unequivocal fashion. It was found that his equations gave conservative estimates of the actual results; the sensitivity of his predictions to the choice of the disposable parameters was also explored, and found to be extreme, but always on the conservative side. This work has been published (4).

c) Crack Nucleation

i) Low Strain Fatigue Crack Nucleation

The investigation of strain localization in copper single crystals, described in section a(iii), pointed up the usefulness of two-beam interferometry in studying crack nucleation. A random slip process was clearly observed to operate within active components of the macroscopic slip bands. However, the emphasis placed on studying deformation mechanisms limited the time available to exploit that tool. Careful investigation, involving much larger numbers of cycles is needed to arrive at a firm understanding of the crack nucleation process. It should be noted that the strain localization discovered in single crystals should be similar to that which is believed to operate in aluminum alloys (1, 2), and consequently any discovery about nucleation in single crystals should have wide application to other kinds of materials.

ii) High Strain Crack Nucleation

Of many mechanisms hitherto suggested to explain crack nucleation at high strains, only one currently holds up to the existing body of results at ambient temperature, namely, a crack forms as a result, first, of inhomogeneous plastic flow (via, for example, incompatible deformation of adjoining grains) which induces surface puckering in the earliest stages of cycling (rapid hardening) and second, of gradual deepening and sharpening of pucker marks into creases capable of concentrating plastic strain and propagating a crack. The second stage is believed to occur during saturation. A 'plastic instability' model of crack nucleation treats the puckering process as one dependent only on the geometrical effects of plastic deformation and not markedly dependent on the material. To test the model, we are exploring puckering processes in detail by two beam interferometry, and by a variety of cycling experiments. For example, virgin annealed specimens were studied with the interferometer from the first cycle until saturation and crack nucleation occurred; the same specimens were then lightly machined and the surfaces repolished. The specimens were thus already saturated when cycling was resumed, and we were then interested to discover extremely rapid crack nucleation, mainly at the grain boundaries, and at the same sites as in the virgin samples. These observations throw doubt on many aspects of the puckering process hitherto considered acceptable. To identify the mechanism of crack nucleation more securely, we are making statistical comparisons of fatigue lives between virgin samples and saturated samples provided with virgin surfaces, and also with samples periodically annealed to eliminate the saturation condition. In addition, we are attempting by Laue techniques to identify the nature of the specific boundaries which provide crack nuclei (orientation of the boundary with respect to the stress axis, misorientation of the grains, and grain orientation with respect to the fatigue axis). Since the interpretation of these results is still in progress, no publication has yet been offered (14).

iii) Fatigue of Ferroelastic Material

The original aim of this project was to explore the fatigue behavior of a ferroelastic material, specifically Cu-Al-Ni, for the special effects of reversible plastic deformation and the light they might shed on crack nucleation mechanisms. This aim was undermined by the success of the copper single crystal project described in Section a(iii) and by the difficulties we encountered in handling Cu-Al-Ni and making it perform in a ferroelastic manner. With continuing experience of the material, the difficulties were overcome, and a fatigue project of polycrystalline Cu-Al-Ni has now been completed. The main failure mode has been found to be intercrystalline and the general fatigue properties have been thoroughly explored. One most interesting result is the fact that Coffin-Manson behavior is obeyed irrespective of the nature of the plastic deformation, i.e., whether it is ferroelastic or regular slip. This work is now ready for publication (13).

8. List of Publications

1. C. Calabrese and C. Laird "Cyclic Stress-Strain Response of Two-Phase Alloys, Part I: Microstructures Containing Particles Penetrable by Dislocation", Mat. Sci. and Eng., 13 (2) (1974) pp 141-158.

2. C. Calabrese and C. Liard "Cyclic Stress-Strain Response of Two-Phase Alloys, Part II: Particles Not Penetrated by Dislocations", Mat. Sci. and Eng., 13 (2) (1974) pp 159-174.

3. C. Calabrese and C. Laird "Comments on Cyclic Stress-Strain Response of Two Phase Alloys", Mat. Sci. and Eng., 15 (1974), pp 95-98.

4. C. Calabrese and C. Laird "High Strain Fatigue Fracture Mechanisms in Two Phase Alloys", Met. Trans., 5 (1974) pp 1785-1793.

5. C. Laird "Cyclic Deformation of Metals and Alloys", in Plastic Deformation of Materials, Ed. R. Arsenault, Academic Press, Inc., in press.

6. C. Laird "Alloy Design in Fatigue", ASM/AIME Symposium, Fall 1974, Eds., G. S. Ansell and J. Tien, in press.

7. K. Shinohara and C. Laird, "Cyclic Response of Al-4% Cu Alloy Under Variable Strains", in preparation.

8. K. Shinohara and C. Laird, "Dislocation Microstructure Produced in Copper by Incremental Cyclic Loading", in preparation.

9. J. M. Finney and C. Laird, "Strain Localization in Cyclic Deformation of Copper Single Crystals", Phil. Mag., 31 (2) (1975) pp 339-366.

10. J. M. Finney, C. Laird and R. de la Veaux, "Bulk or Surface Control of Cyclic Hardening?", Submitted for publication.

11. C. Laird, J. J. Finney, A. Schwartzman and R. de la Veaux, "History Dependence in the Cyclic Stress-Strain Response of Wavy Slip Materials", submitted for publication.

12. C. Calabrese and C. Laird, "Cyclic Response of Metals and Alloys", 3rd Int. Conf. on Fracture, Munich, 1973, paper V-231.

13. N. Yang, C. Laird and D. P. Pope, "Fatigue of Ferroelastic Cu-Al-Ni Alloy", in preparation.

14. W. Kim and C. Laird, "Crack Nucleation in High Strain Fatigue", in preparation.

9. List of Scientific Personnel

Principal Investigator - Campbell Laird - major support

Post-Doctoral Student - K. Shinohara - complete support

Graduate Students

Name	Support	Degree obtained
C. Calabrese	Partial	Ph. D.
M. Curovic	Complete	Failed to meet requirements
J. M. Finney	Partial	Ph. D.
W. Kim	Partial	Ph. D. (anticipated)
N. Yang	Partial	M. S. E.
S. Herd	Complete	Ph. D. (anticipated)